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Some Shallow Water Inferences from the Celtic Duet Experiment

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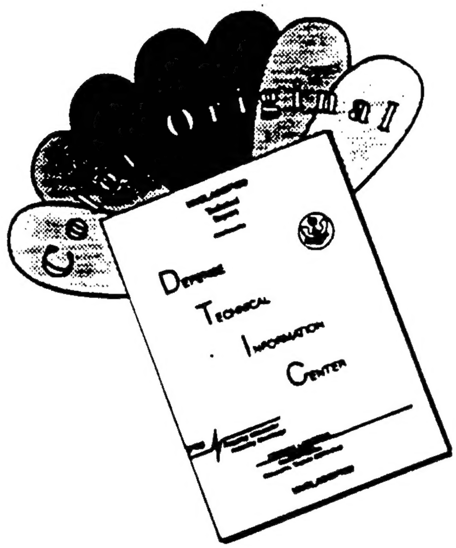

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ABSTRACT

Scattering strength estimates are made for selected CW (Continuous Wave) and HFM (Hyperbolic Frequency Modulation) pulses of different lengths. Three shallow water experiment areas of the 1992 Celtic Duet experiment of the southwest approaches are discussed. These include a site with a more complex mixture of sand, chalk, and limestone, a site with mostly sand (and sand waves), and a site with mostly chalk. Examples of the spatial character of the reverberation are presented. Comparisons of reverberation data with GSM (Generic Sonar Model) runs are discussed. Statistics of selected reverberation beam time series are compared with a pure Rayleigh distribution. One way signal spreading using OASES (Ocean Acoustics and Seismic Exploration Synthesis) broadband modeling predictions are discussed and inferences for two way reverberation are made.

EXECUTIVE SUMMARY

This work represents a brief study of towed array reverberation data taken during the 1992 Celtic Duet sea trial. The data discussed here are near 400 Hz from 3 shallow water sites (100 - 150 m) of the southwest approaches (SWAP) to the French/English channel area. The study describes 3 separate areas of investigation: towed array beam time series reverberation data/model comparisons, towed array beam reverberation statistics, and shallow water waveguide induced pulse spreading. Findings for the reverberation data/model comparisons are that Site A, (the chalk limestone site) was well modeled by a geoacoustic half space of a chalk/sand mix, and a Lambert's Rule coefficient of scattering strength = -29 dB. This was good over all three relative look directions studied, and for both a 2.4 second HFM and an 8 second CW. For Site B (the permanent sand wave site) the reverberation data were well modeled by a hard sand like geoacoustic half space with a Lambert's Rule coefficient = - 24 dB. This was also good over all three look directions studied for Site C (preliminary investigation). Results are consistent with a geoacoustic model like Site A, but with a scattering coefficient of -24 dB. For the pulses analyzed here, no pulse length dependence or azimuthal dependence of scattering strength was observed. Investigation of beam statistics at Sites A and C using 8 second CW pulses showed that Site C was Rayleigh but Site A gave a non-Rayleigh distribution. The observation is made that shear losses at the water bottom interface are important at 400 Hz for these environments and ignoring them can result in underestimation of bottom scattering strengths.

LIST OF FIGURES

INTRODUCTION AND EXPERIMENT OVERVIEW

In July 1992, the SACLANTCEN (Strategic Allied Commander Atlantic Undersea Research Centre) conducted a series of shallow water reverberation and propagation loss measurements jointly with the Naval Research Laboratory (NRL). The sea trial was called Celtic Duet (or Swamp III by NRL) and was conducted in the southwest approaches area of the English-French channel.

The experiment is described in detail in a SACLANTCEN report by Ellis, et. al [1]. Extensive environmental data were gathered during this trial. A separate trial to study the geoacoustic character of the area was conducted immediately after Celtic Duet by SACLANTCEN.

This white paper discusses selected reverberation data taken near 400 Hz by the SACLANTCEN's R/V ALLIANCE towed arrays at three different sites varying between 100 and 150 m depth, see Figure 1. According to Max, et. al [2], the first Site (A) was flat and contains a mixture of sand, limestone, and chalk. The second Site (B) contains encrusted, long period fixed sand waves oriented ~ 110/290°T. The third Site (C) was flat also and contains mostly chalk.

Figure 2 shows a typical sound speed profile during this experiment. The actual profile for each day varied mostly in the location of the knee in the profile which varies anywhere from 15-35 m deep over the 20 days of the experiment. In what is shown, data were collected on towed arrays using 64 or 128 elements spaced at 1 m (Hann shading was used).

This paper discusses three separate aspects of these shallow water data. The first part discusses the reverberation data and GSM (Generic Sonar Model [3]) data/model comparisons. The second part deals with beam fluctuations statistics and how and when they were found to deviate from Gaussian behavior. The last part deals with some broadband modeling of pulse propagation at Site A and discusses pulse spreading.

RESULTS

A. REVERBERATION DATA AND MODEL DATA COMPARISONS FOR CELTIC DUET

In this section we look at selected beam time series data near 400 Hz taken from the SACLANTCEN towed arrays. Our first examples are from Site A. Due to space limitations we will only show a small amount of the data analyzed. Figure 3 shows a sample polar plot of beam reverberation and noise versus location for 1 HFM pulse at Site A. The local bathymetry overlays the reverberation and noise plot. The pulse was 2.4 seconds long and spanned 365-425 Hz. The long vector on the plot indicates ship heading (233°T) and the circle is a 60 second marker circle after pulse start. One can see the discrete return from the shallow feature NW of the array. One also sees very anisotropic noise from shipping noise (the radial lines outward from the source). The data are represented by the fluctuating solid lines. Figure 4 shows a model data comparison using GSM for the same pulse for a beam looking 45° aft of broadside. To get the GSM to agree, we used a forward model and match approach, starting with geoacoustic models that others used on some of this data previously (Deshamais [4], Caiti, et. al [5]). After going through many perturbations, we arrived at a bottom loss versus grazing angle curve shown in Figure 5 (using the OASES model [6, 7] with shear). This curve was put into GSM to achieve the match shown. The final geoacoustic model that gave the best match at Site A to reverberation near 400 Hz was a simple half space with compressional and shear velocity C_p, C_s of 1720 and 675 m/s respectively and compressional and shear attenuation α_p, α_s of .3 and .6 dB/ wavelength and a density ρ of 2.2. This is consistent with the sand-chalk-limestone mix reported by Max [2]. The match is not very sensitive to density for these data. The GSM forward model and match approach gives a Lambert's Rule coefficient of μ = -29. We found the bottom type and the Lambert's Rule coefficient (μ) good for both an 8 second long CW pulse and the 2.4 seconds HFM (no pulse length dependence on μ). We also found these parameters gave a reasonable match at 3 relative look directions: broadside, 45° aft, and aft end fire (no azimuthal dependence to μ either). One observation here is that c_s = 675 m/s is fairly high compared with typical environments. One other area of investigation may be that if layers with velocity gradients were used rather than a simple half space a similar match might be obtainable with a different geoacoustic characterization. Note that on Figure 4 from 20-60 s there were nonstationary noise and discrete reverberation returns causing the data to be a bit higher than the model in this look direction, but still a good match overall to the other look directions (not shown).

At Site B, Figure 6 shows a sample of beam power versus location on a quiet sea state day (wind speed ~ 5-12 knots). Again the bathymetry overlies the plot showing the fixed sand wave structure. Some reflections off the sand waves nearby can be seen (near the contour labeled 120 m, NW of the source). This example is from a 2.4 second HFM pulse sweeping from 375-395 Hz. Figure 7 shows a 45° aft beam model/data comparison using a Lambert's Rule coefficient

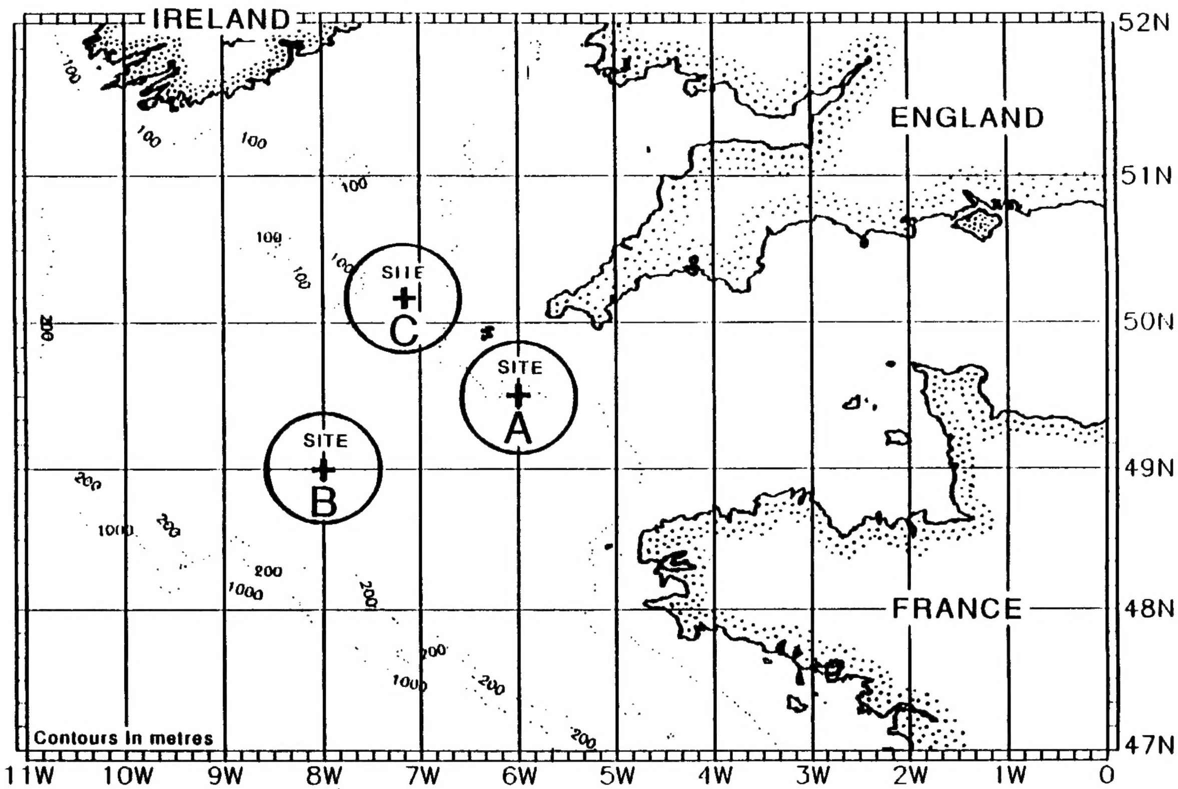

Figure 1. Celtic Duet Experiment Sites

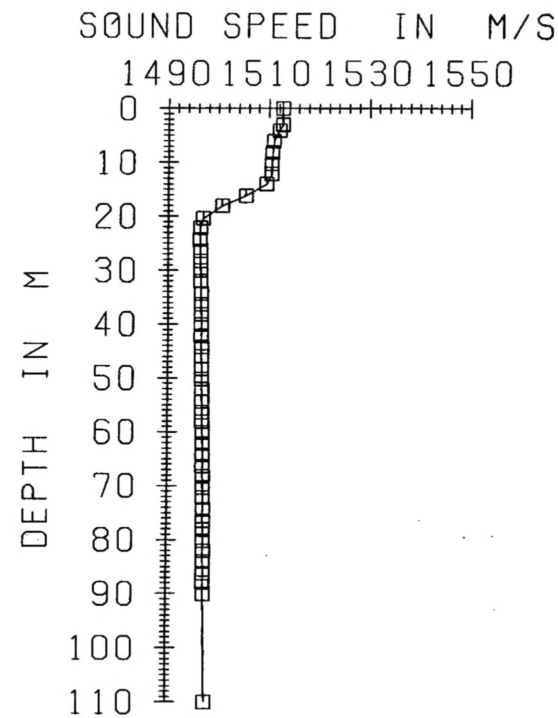

Figure 2. Typical sound speed profile during Celtic Duet

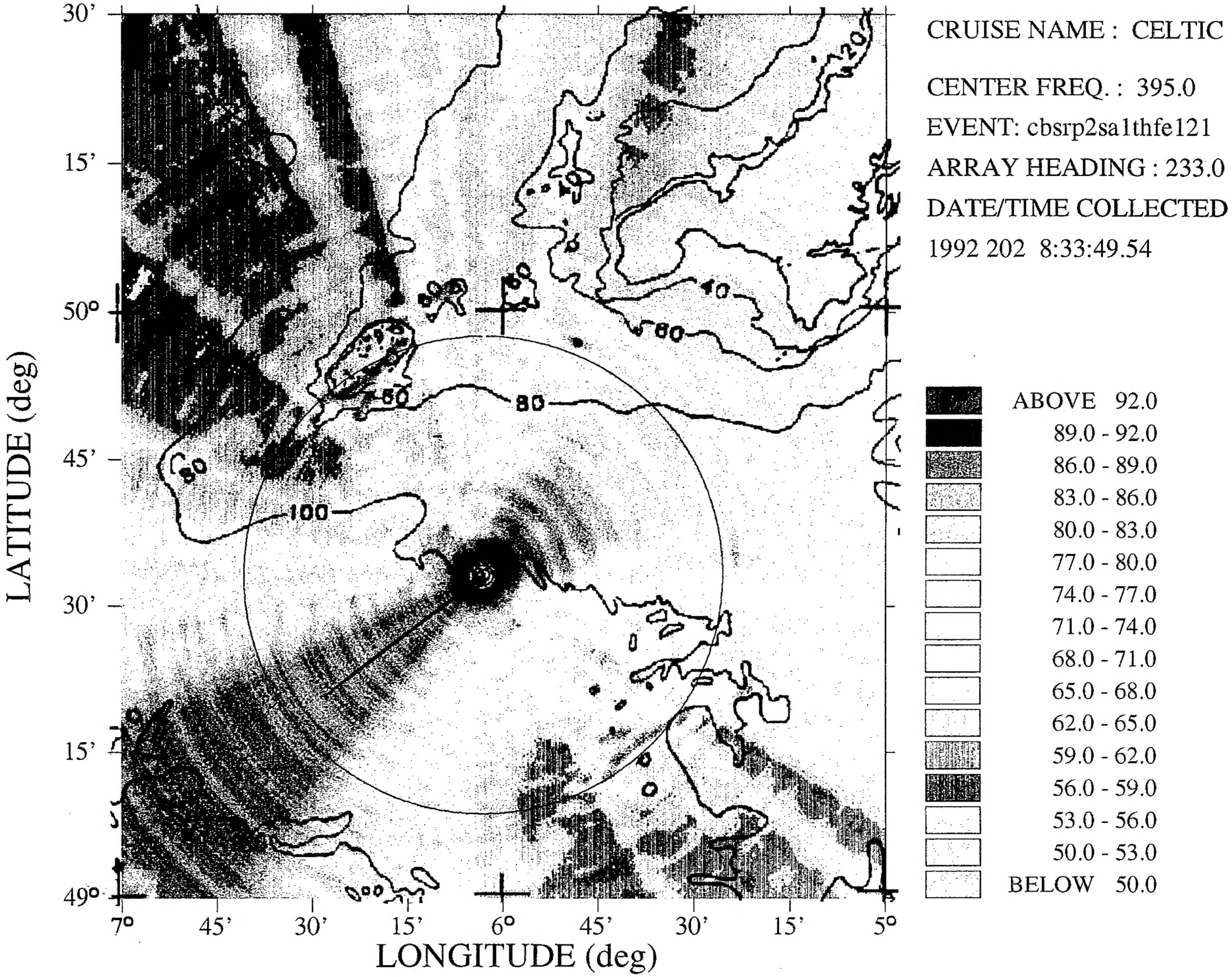

Figure 3. Received beam power versus location for a 2.4 second HFM pulse

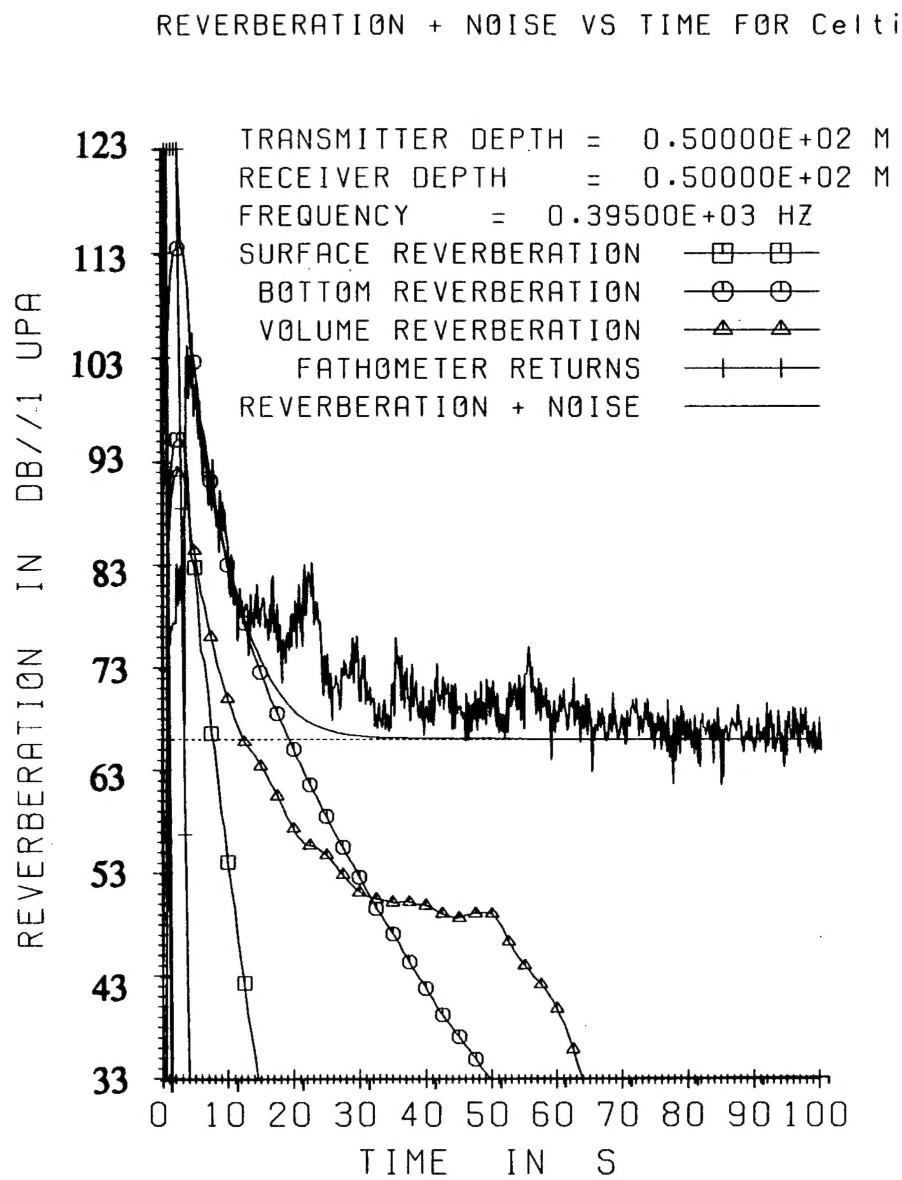

Figure 4. Data versus GSM predicted reverberation.
Site A, Aft 45 Deg. - 395 Hz - H12 HFM, POLYG.2, Leg 1, 20-JUL

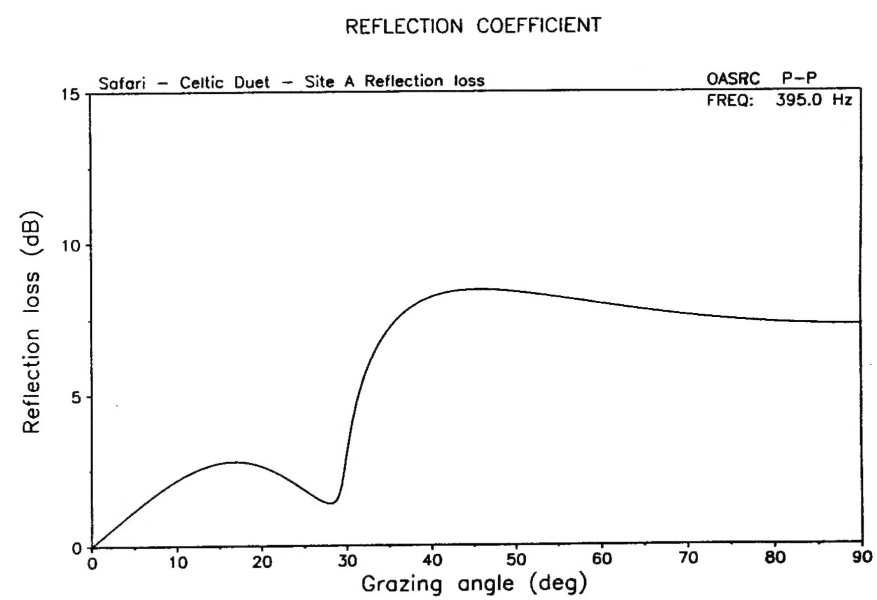

Figure 5. Reflection loss versus grazing angle for best geoacoustic match to reverberation data

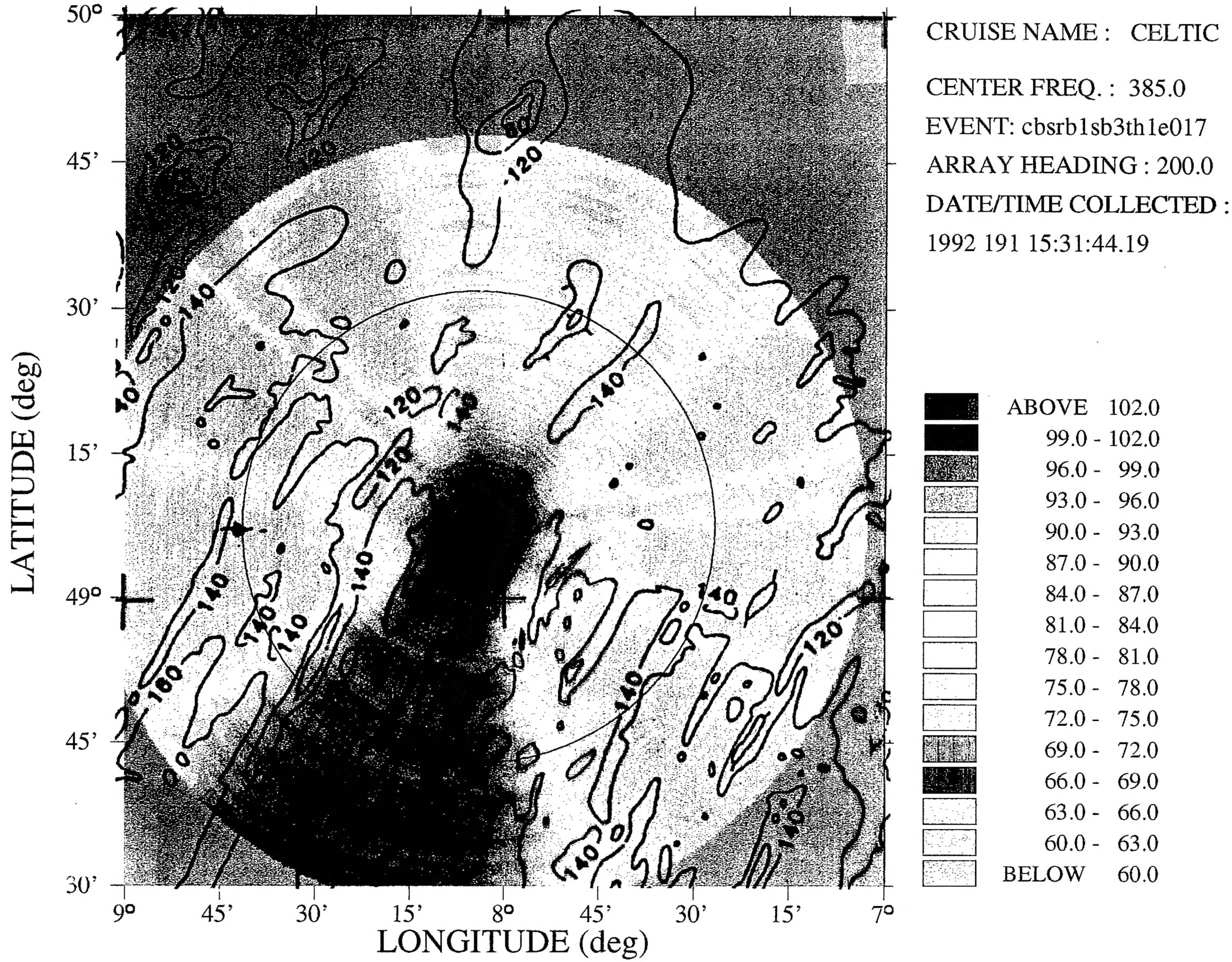

Figure 6. Received beam power versus location for a 2.4 second HFM pulse

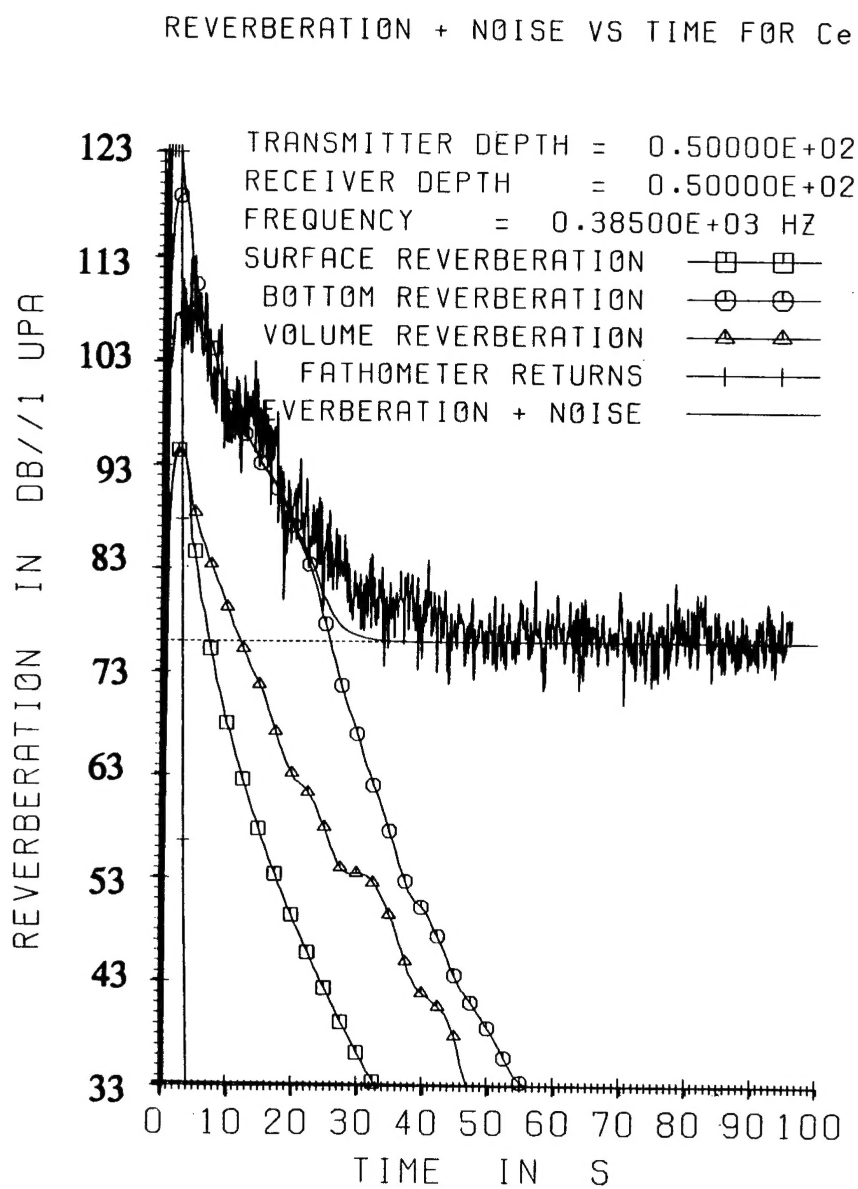

Figure 7. Data versus GSM predicted reverberation. Site B, 45 Deg. Aft - 385 Hz - H1, B1, Leg 3, 9-JUL

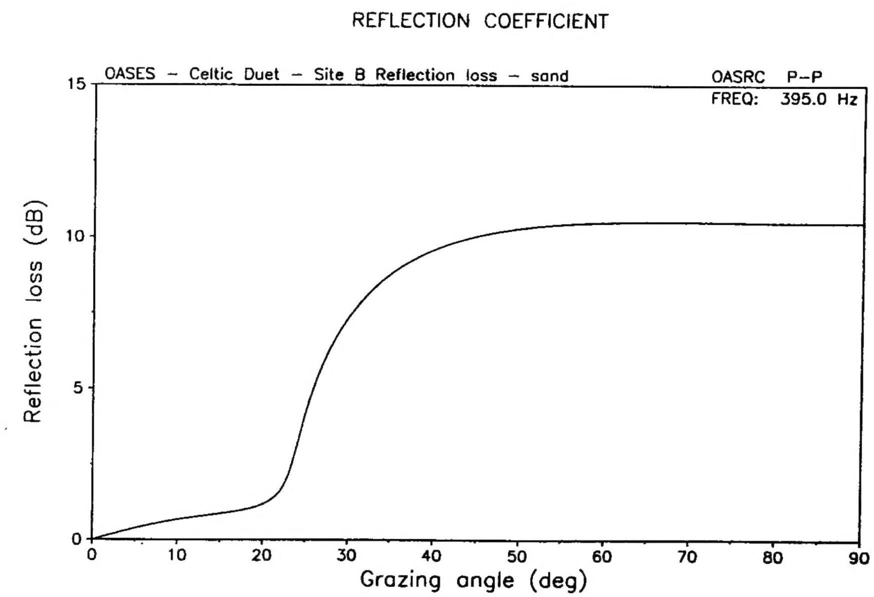

Figure 8. Reflection loss versus grazing angle for best geoacoustic match to reverberation data

of μ = - 24 and a sand like bottom. The best reflection loss versus grazing angle curve (again from the OASES model using shear) is shown in Figure 8. The geoacoustic model that produced this curve was c_p = 1650, c_s = 300, α_p = .5, α_s = 1.7, ρ = 1.7 (a hard sand like bottom) which is reasonably consistent with Max's observation that the permanent sand waves in this area were encrusted. Figure 9 shows a 45° aft beam model/data comparison two days later for the same HFM pulse as Figure 7 when the wind speed jumped up to ~ 25 knots. The same geoacoustic bottom model and same Lambert's Rule coefficient were used in GSM (- 24 dB) but the actual sound speed profiles of the day were used for each GSM run. (The location of this pulse is close to the previous case too.) This model fit all three beam directions (broadside, 45° aft, and aft endfire) so after changing the wind speed, the GSM model matched both the July 9 (wind speed = 9) and July 11 (wind speed = 25 knots) data sets for this HFM pulse. Again no azimuthal dependence on μ was observed (excluding prominent bottom features).

A quick look at the same HFM pulse at Site C (15 knot wind speed) produced the match shown in Figure 10. This is preliminary but the data were well matched using the same bottom loss versus grazing angle curve as for Site A and a Lambert's Rule coefficient of μ = - 24 dB. Max said this site was mostly chalk but the match here suggests the effective compressional and shear speeds may be more like a sand-chalk mix.

It should be noted that all the data here seem to be well modeled using a Lambert's Rule ($\sin^2\theta_g$ dependence on θ_g, the grazing angle) rather than what may be more common in shallow water - a linear $\mu \sin\theta_g$ dependence (see [8] for example).

One final very important observation should be made. When modeling Site A we started with Desharnais results using a shear speed of c_s = 350 m/s (much slower than our final best match of 675 m/s) and looked at predicted transmission loss with and without shear velocity from a source at 46 m to a receiver on the bottom (108 m). Figure 11 shows that (from OASES) at the bottom we observe ~ 10 dB more loss with shear at ranges beyond ~ 20 km. Not shown is the fact that for a hydrophone 8 m off the bottom, OASES predicts no difference in propagation loss with and without shear at 400 Hz. The important point is that propagation models using fluid only computations (like GSM) can underestimate scattering strengths by significant amounts if shear is important and if shear is not factored in elsewhere (like using corrected bottom loss versus grazing angles curves). This effect can change scattering strength estimates significantly but it is strictly a propagation loss effect.

B. SELECTED BEAM STATISTICS FOR CELTIC DUET

In this section we present an illustration of beam time series statistical fluctuations which are observed in shallow water (courtesy of Deliman [9]). Figure 12a shows a sample broadside beam reverberation time series from an 8 s CW ping at 400 Hz at Site A. This data was taken in 108 m of water over a bottom of mixed composition composed of some chalk, limestone, and sand. Shown in the figure are two time intervals selected for reverberation only and noise only processing. When the noise only portion is averaged over 13 separate independent beams within ± 45° of the broadside look direction, Figure 13a results. This figure shows log (1 minus the cumulative probability density function) labeled probability of false alarm or PFA versus the normalized amplitude for 10 separate pulses. As expected when the noise is a Gaussian random variable, the amplitude distribution obeys a Rayleigh distribution. Figure 13b shows what happens when the reverberation segment is processed in a similar fashion. Here the spiky returns of Figure 12a result in the PFA curve for this reverberation segment being higher than a Rayleigh distribution and consistent with a bi-modal amplitude distribution.

When three similar figures were generated for the same pulse type taken at Site C, (mostly chalk with water depth ~ 115 m and 20 knot wind speeds) quite different results were observed. Figure 12b shows a time series again for a broadside beam with approximately the same time segments for reverberation and noise processing taken as done for Figure 11a. Figure 14a shows an average of 13 beams in each of 4 pulses and one can see the noise is still Rayleigh but Figure 14b shows that the reverberation is also Rayleigh. Going back to the original time series we see that the reverberation portion is less spiky than in Figure 12a. This seems to imply it is more like a decaying Gaussian pressure field than was the case at Site A, and that when normalized by the time varying mean, the distribution is unimodal.

C. PULSE SPREAD AND BROADBAND MODELING OF THE CELTIC DUET ENVIRONMENT

In this section, we summarize predicted pulse spreading for Site A using broadband modeling with the OASES model. These results were taken from [10]. For this example, we use environmental inputs from the Celtic Duet sea trial (1992). The example is taken at Site A with 108 m water depth. The profile is downward refracting between 0 and 20 m with a distinct "knee" at 15-20 m. After that there is a slightly positive sound speed gradient (see Figure 2). Using the

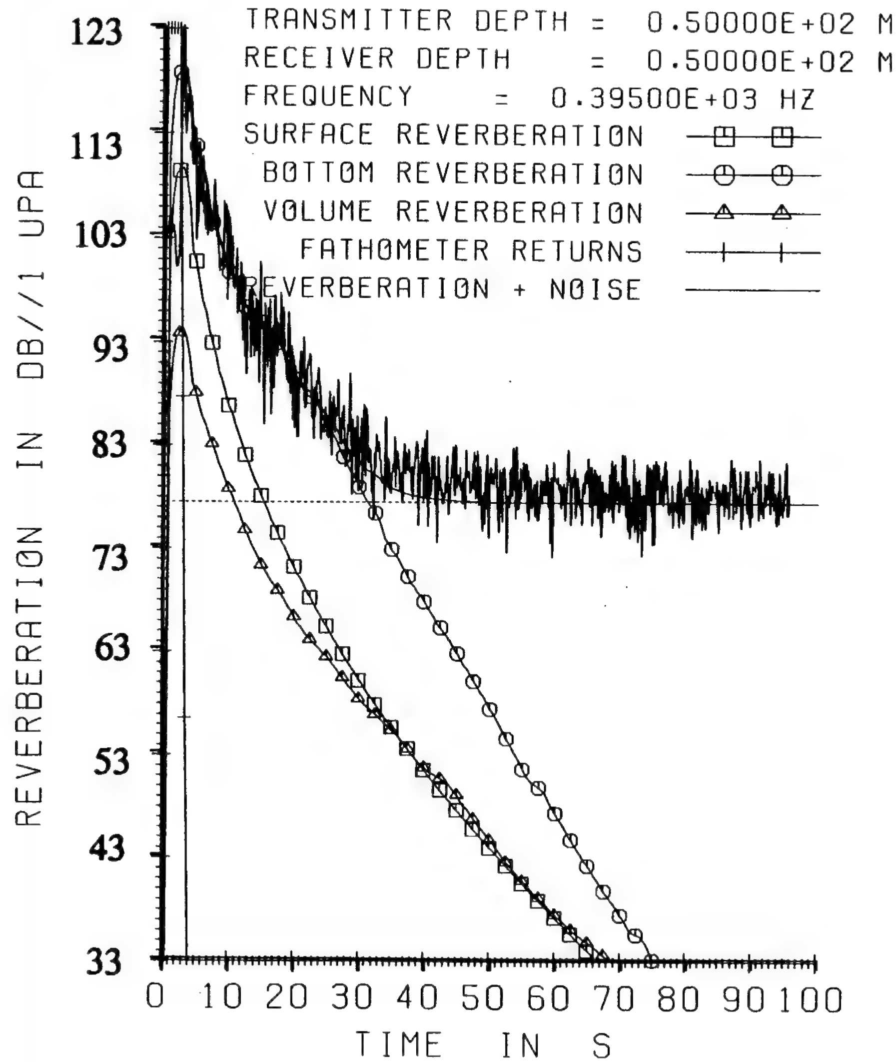

Figure 9. Data versus GSM predicted reverberation. Site B, 45 Deg. Aft - 385 Hz - H1, B2, Leg 3, 11-JUL

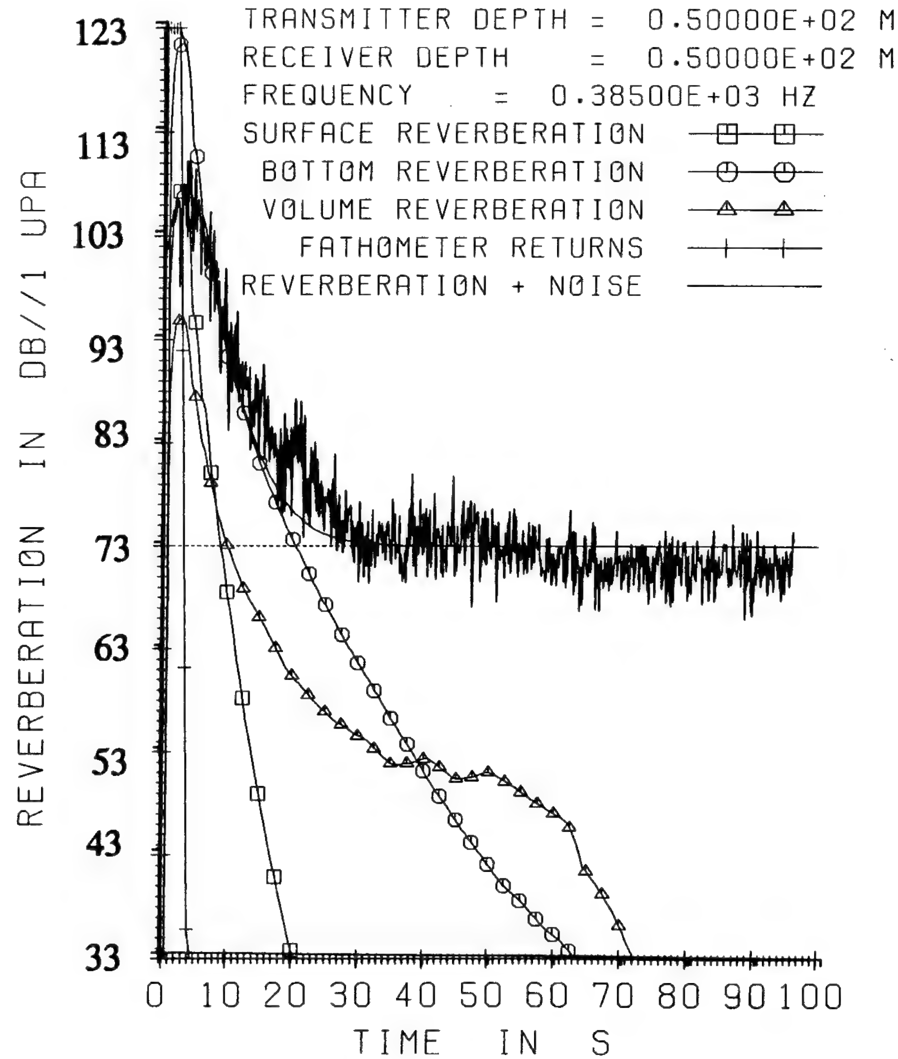

Figure 10. Data versus GSM predicted reverberation. Site C, 45 Deg. Aft - 395 Hz - H1, C1, Leg 1, 15-JUL

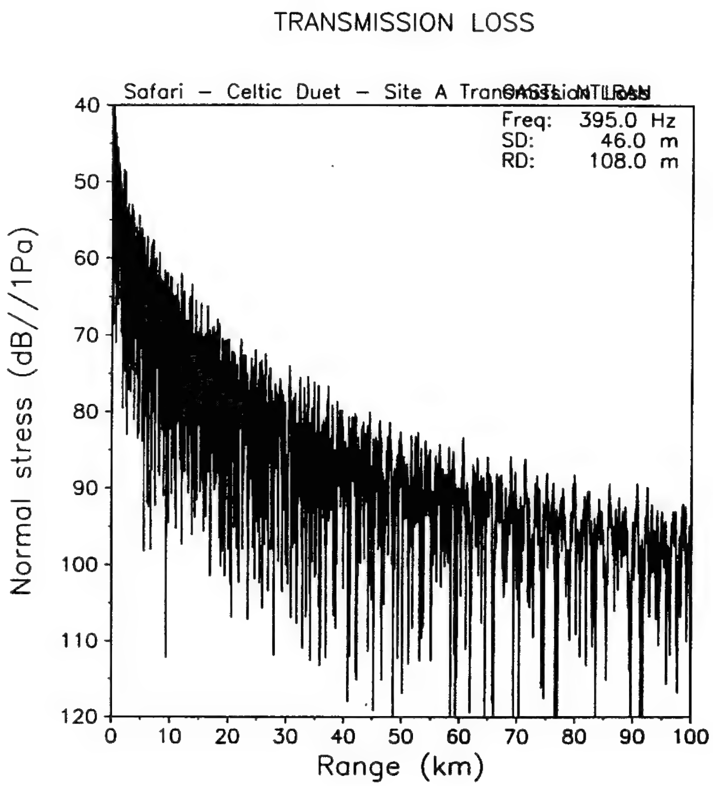

Figure 11a. Propagation loss from 46 m source to receiver at the bottom with shear effects included

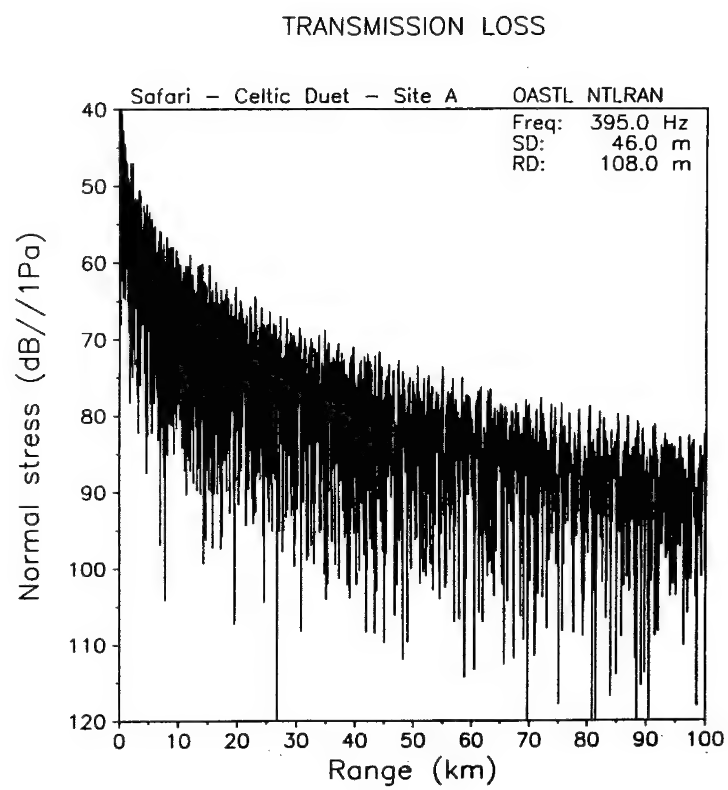

Figure 11b. Propagation loss from 46 m source to receiver at the bottom with no shear effects included

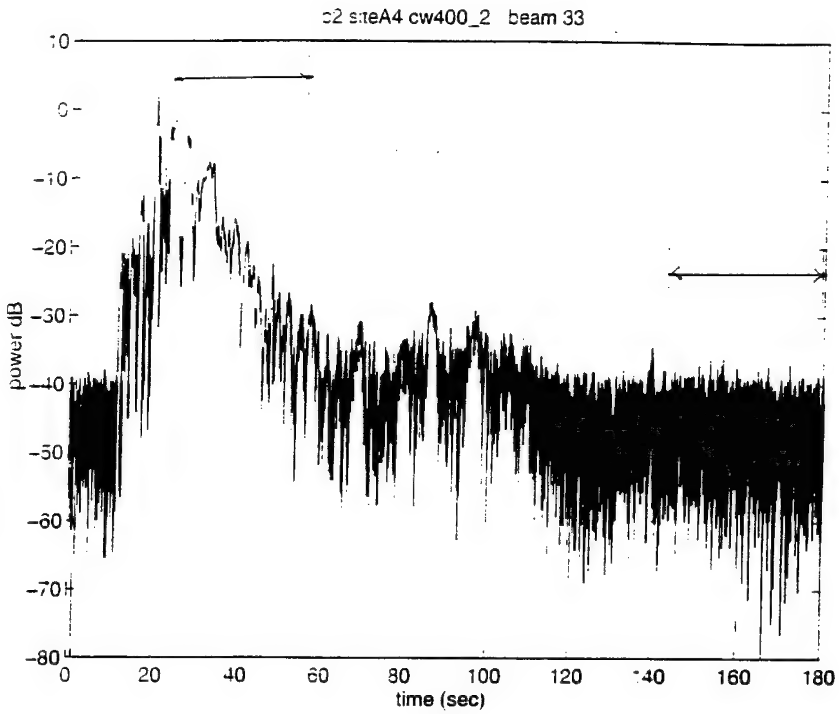

Figure 12a. Representative reverberation 400 Hz CW from Site A of Celtic Duet, a chalk and sand bottom. Portion of the recording used to compute statistics are shown. Time was subsampled, using every 20th point only.

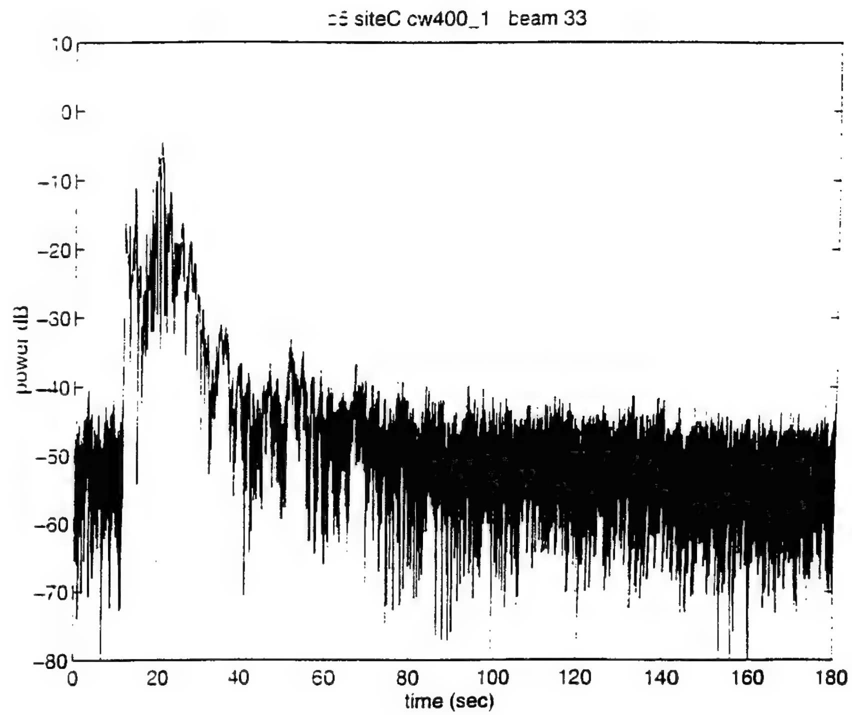

Figure 12b. Representative reverberation 400 Hz CW from Site C of Celtic Duet, a chalk bottom

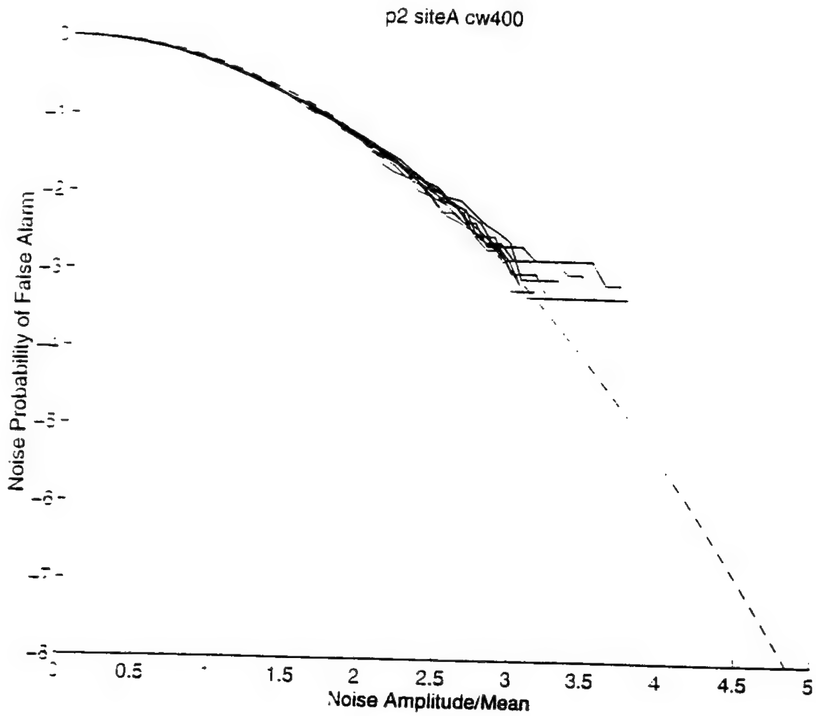

Figure 13a. Statistics from 10 separate pulses windowed in the noise portion at Site A. Dashed line is Rayleigh

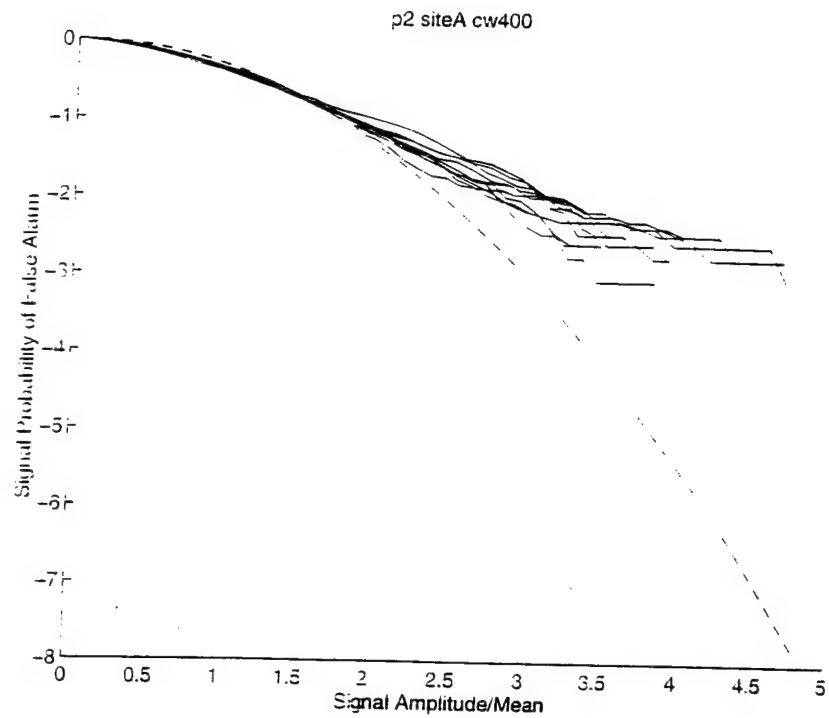

Figure 13b. Statistics from 10 separate pulses windowed from the signal portion at Site A. Dashed line is Rayleigh

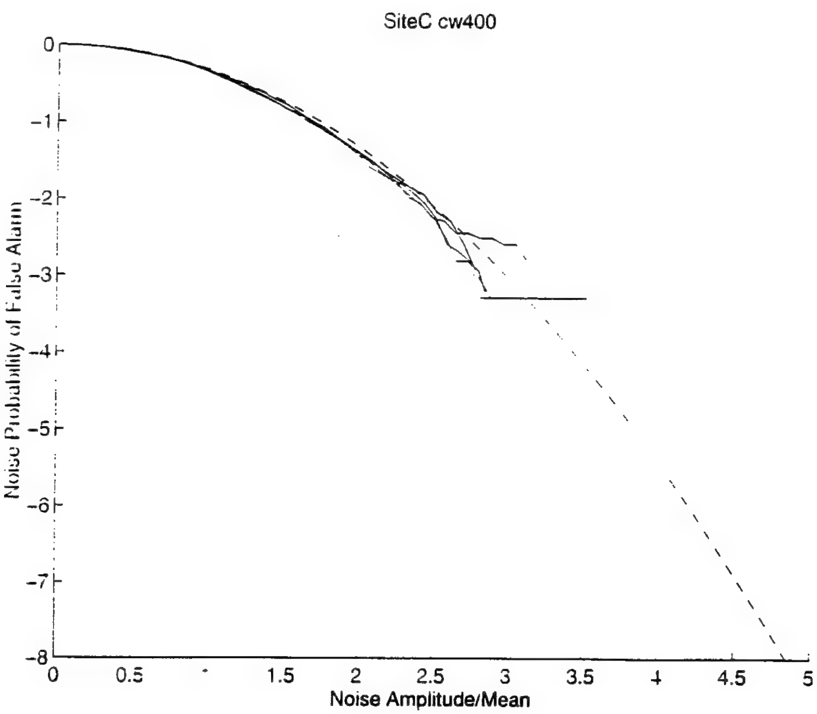

Figure 14a. Statistics from 4 separate pulses windowed from the noise portion at Site C. Dashed line is Rayleigh

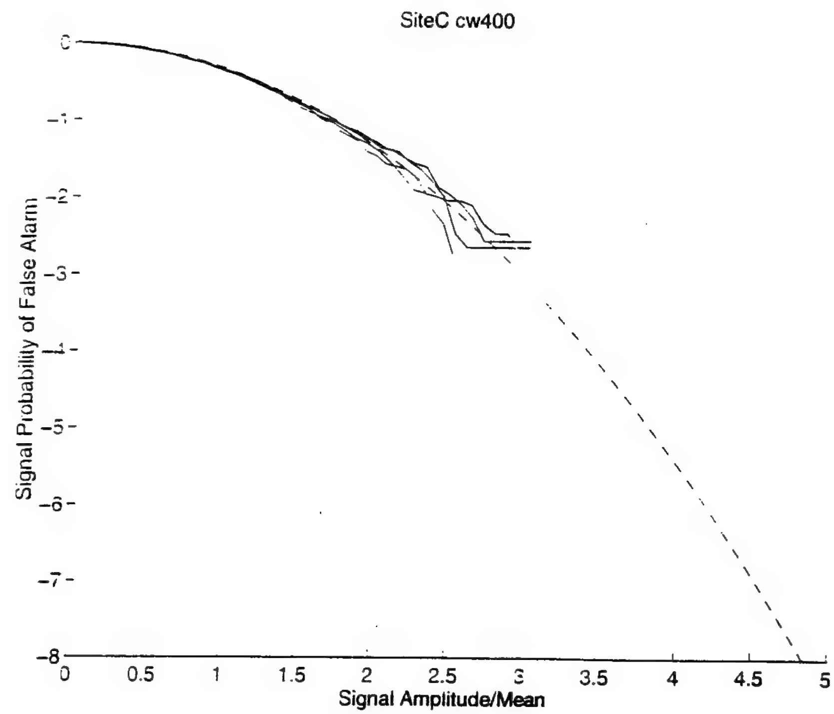

Figure 14b. Statistics from 4 separate pulses windowed from the signal portion at Site C. Dashed line is Rayleigh

OASES model with measured CTD data, this profile was simplified and broken into 15 range independent horizontal layers with gradients, except for the last layer which was modeled as an elastic half space to represent the bottom. (The geoacoustic model was the same as that used by Dehamais [3] to produce good model/data agreement with the measured propagation loss. This work used c_s = 350 m/s, a lower shear speed than was found in Part A to match the observed reverberation time series.) Recall that the bottom was characterized by Max [2] as a sand, chalk, and limestone mix. With these inputs one can choose a simple two-cycle wavelet from OASES and make predictions of signal spreading and of the received time series pulse. This input wavelet and its power spectrum (with most energy contained in the ~ 60 - 180 Hz band) are shown in Figure 15a and 15b. A source depth of 46 m was selected and OASES was used to create a channel transfer function at four different range steps. The pulse is convolved with that function and a plot of pulse shape versus range results as shown in Figures 16 and 17, the first for a receiver at the bottom and the second for a receiver at ~ 28 m. One can see for each receiver depth there is a comparable overall signal length. However, the details of each of the eight predicted time series are quite different. In this example we see signal lengths of ~ .6 s at 8 km and lengths closer to .8 s at 18 km. The simulation results in [10] showed signal elongations from 2 to ~ 60 times transmitted pulse length of 30 ms at 8 km when testing 10 different shallow water environments in the same frequency range. One can expect these elongations to double for monostatic backscatter. These plots are linear in amplitude so the "significant" elongation will probably appear to be less if shown on a dB plot. A somewhat different look at the predicted signal is shown in Figure 18 which shows predicted depth dependence every 2 m. The modal interference structure is very evident in this type of plot. In addition, as expected, the pulse detailed shape, envelope, and overall observed length varied significantly from one environment to the next. There was modal interference structure observable in the depth dependence plot from many of the environments simulated. It is important to note that the highly detailed time series plots contain absolutely no stochastic effects and so details in the structure should be expected to be different when these types of random phase modulations are introduced.

CONCLUSIONS

- Shear may play a critical role in estimation of scattering strength. A 9 dB difference in propagation loss with and without shear shown for Site A at 400 Hz means scattering strength could be underestimated by 18 dB. We need to know what role shear conversion plays at the bottom even at these frequencies. (This is a propagation loss effect not a scattering effect.)

- Based on analysis of a few selected pulses, Site A reverberation was modeled well using GSM with Lambert's Rule coefficient $\mu \sim$ -29 dB and a geoacoustic bottom between gravel and chalk. Site B reverberation was modeled well using GSM with $\mu \sim 24$ and a geoacoustic bottom like a hard sand. Preliminary results for Site C showed that a geoacoustic bottom like Site A but $\mu \sim$ - 24 dB gave a good model/data comparison at Site C.

- Beam fluctuations statistics on an 8 second CW tone at 400 Hz at Site A showed reverberation beam time series to be non-Rayleigh while at Site C these time series were Rayleigh.

- Broadband modeling of 10 selected shallow water geoacoustic environments showed one way pulse elongations from 2 to ~ 60 times transmitted pulse lengths at 8 km for a short 30 ms pulse. One can expect the two way pulse spreading to be at least double the one way spread.

- Broadband modeling also showed significant differences in pulse absorption and dispersion as a function of the water column and geoacoustic environment. These model differences should be expected given the large differences in bottom properties and geometry that are encountered over different ocean regions.

- When prominent bottom features are excluded, no pulse length dependence or azimuthal dependence on scattering strength was observed for the pulses analyzed, even over the anisotropic bottom of Site B with sand waves.

- Certain in situ measurements such as XBTs are essential at each location to obtain critical acoustic parameters for model accuracy.

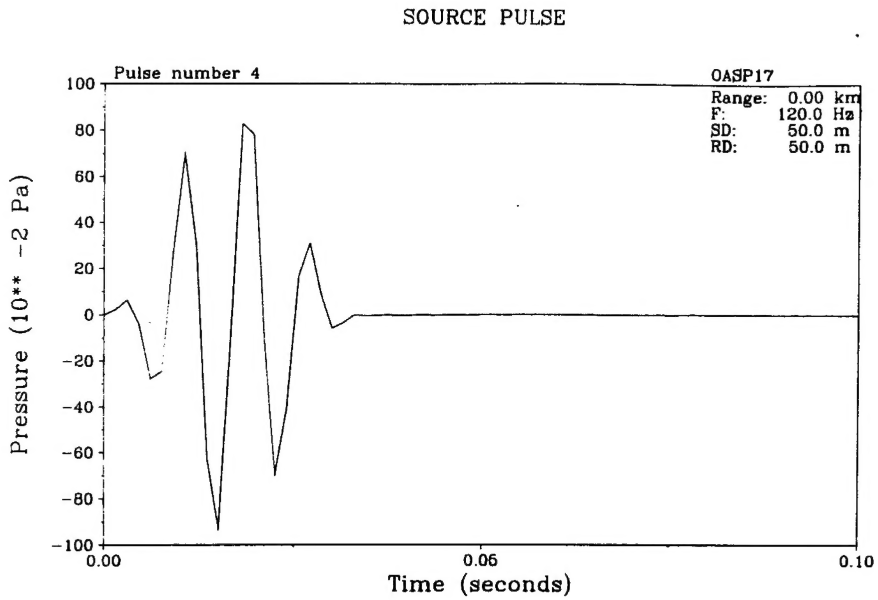

Figure 15a. Time series for the type 4 pulse option in the OASES model

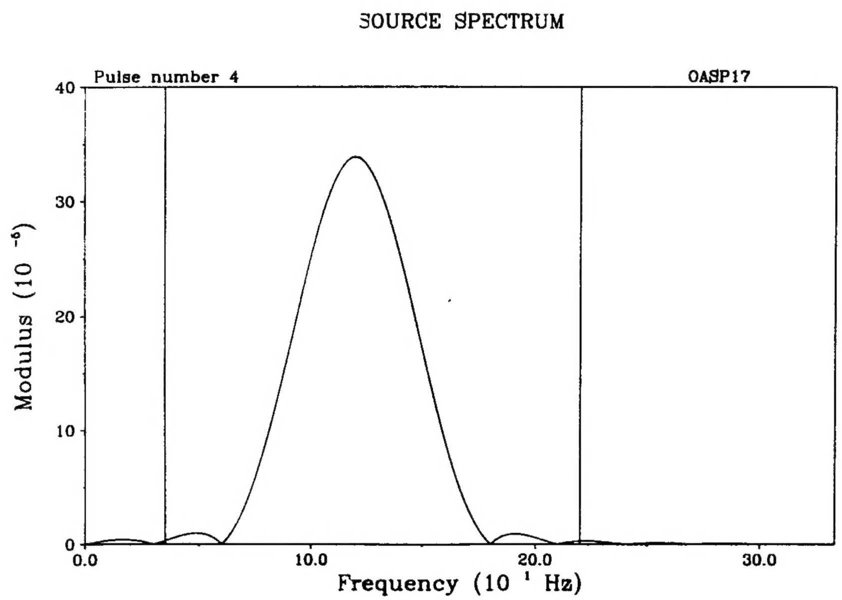

Figure 15b. Spectral level for the type 4 pulse

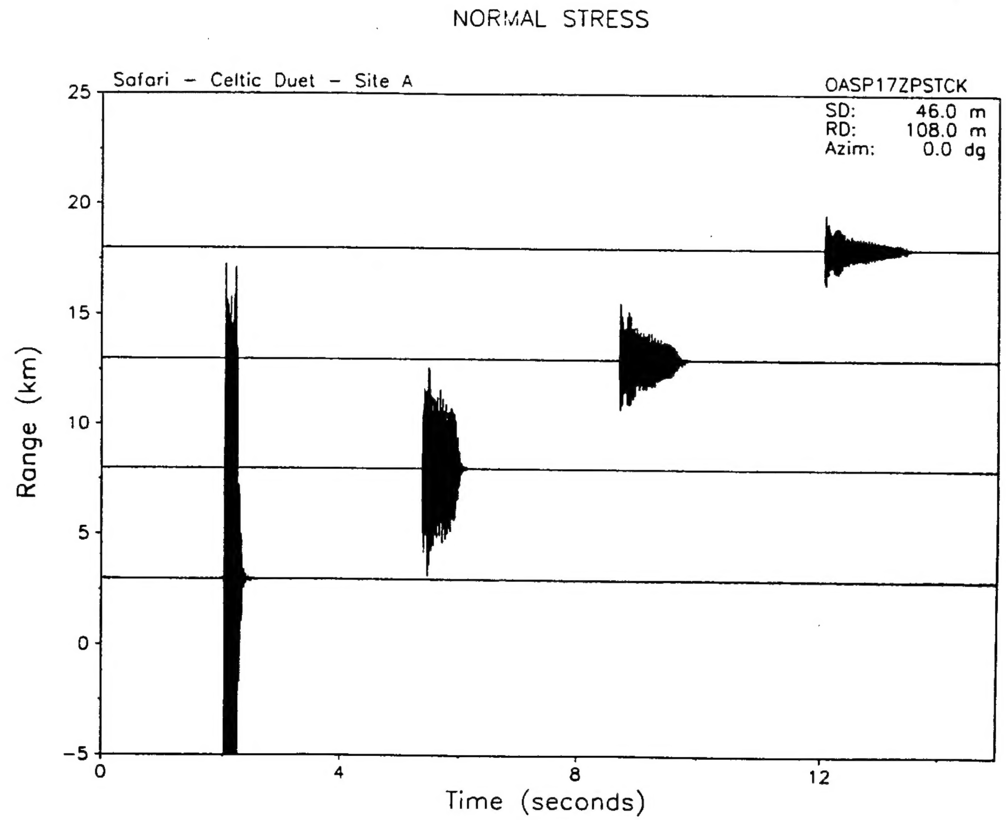

Figure 16. Range dependence of received signal for 108 m receiver (type 4 pulse)

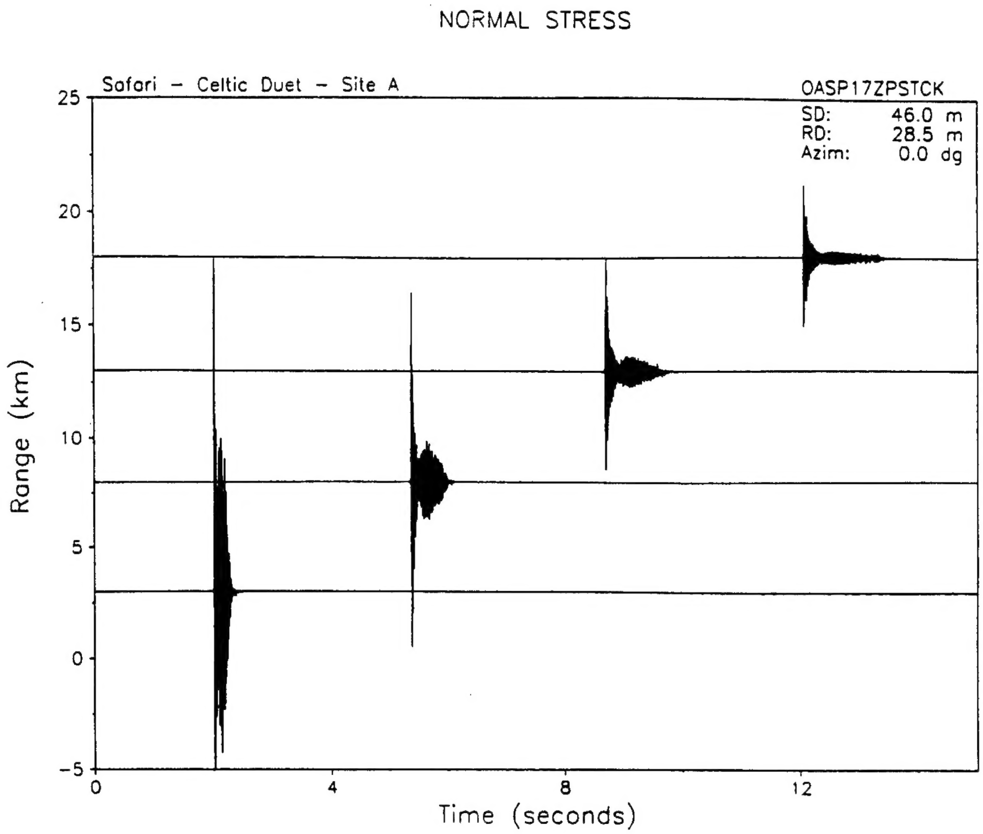

Figure 17. Range dependence of received signal for 28.5 m receiver (type 4 pulse)

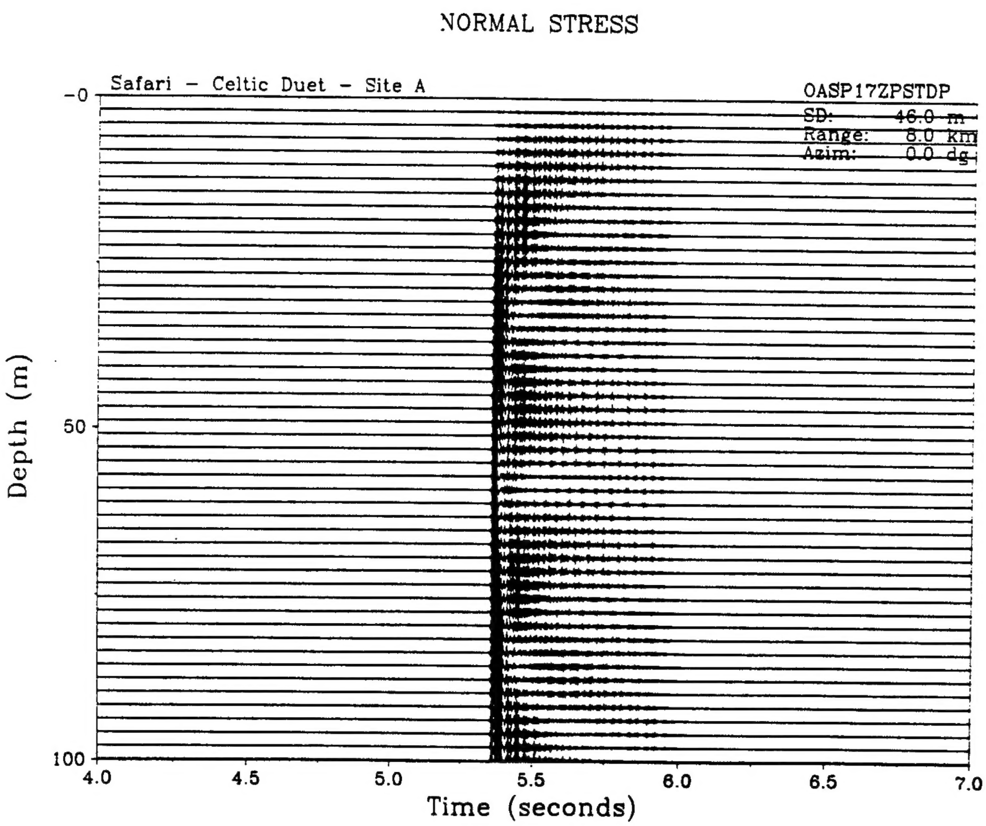

Figure 18. Depth dependence of received signal at 8 km (type 4 pulse) for an array of phones spaced every 2 m over the water column

ACKNOWLEDGMENTS

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